Data Assimilation and Predictability Studies for Improving Tropical Cyclone Intensity Forecasts

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LONG-TERM GOALS

This project aims to understand and improve the forecast of Tropical Cyclone (TC) lifecycle evolution and intensity, focusing on both large-scale environment and mesoscale phenomena in the TC system, which are major components responsible for intensity change. Two major challenges in TC intensity forecasting are the general lack of observations in the vicinity of TCs and the adaptive representation of the forecast error covariance. This project attempts to address both challenges for improving TC intensity forecasting.

OBJECTIVES

Intensive T-PARC (THORPEX[1] Pacific Asian Regional Campaign) observations and other available observations will be assimilated with the LETKF (Local Ensemble Transform Kalman Filter) into the CFES (Coupled ocean-atmosphere general circulation model For the Earth Simulator) and the WRF (Weather Research and Forecasting) mesoscale model to study 1) the characteristics and role of coupled ocean-atmosphere covariance, 2) the impact of each observation assessed by an efficient ensemble sensitivity analysis method, 3) a better way to assimilate observations in the vicinity of the TC center and potential usefulness of Lagrangian data assimilation (LaDA), 4) several new data assimilation techniques to improve the performance of LETKF, and 5) the predictability of TC intensity due to the uncertainty of initial conditions.

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[1] THORPEX (The Observing System Research and Predictability Experiment) is an international research and development program of the World Meteorological Organization (WMO).

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APPROACH

This project has two major components with the CFES and WRF models. LETKF experiments with the CFES model is performed on the Earth Simulator (ES) supercomputer system. First, Co-I Enomoto (Earth Simulator Center) performs data assimilation experiments with the atmospheric part of CFES (AFES: Atmospheric general circulation model For the Earth Simulator). Miyoshi, Enomoto, and Co-I Komori develop the LETKF system with CFES and perform data assimilation and ensemble prediction experiments. Miyoshi and Co-I Yang study the characteristics of coupled ocean-atmosphere covariance and its impact on TC forecasts.

Experiments with the WRF model are performed on the newly acquired cluster server through this project support. First, the WRF-LETKF system is developed by Miyoshi and Researcher Kunii at the University of Maryland (UMD). Data assimilation and ensemble prediction experiments are performed to study the impacts of the T-PARC observations on TC intensity forecasts and predictability. Also, Atmospheric Infrared Sounder (AIRS) satellite data are assimilated. Higher resolution experiments are performed to simulate mesoscale phenomena in the TC system.

Ensemble sensitivity analysis of observations and new data assimilation techniques to improve the LETKF are common to both CFES and WRF components. Miyoshi and Co-PI Kalnay study sensitivity analyses of observations. Miyoshi and Co-I Li work on theoretical developments of adaptive estimation methods of covariance inflation and observation errors. Miyoshi and Co-PI Bishop study adaptive localization methods. Miyoshi and Yang apply the running-in-place method to find its impact on TC intensity forecasts.

WORK COMPLETED

In the component of global data assimilation, in FY2010, AFES-LETKF data assimilation experiments were performed with the Earth Simulator with real observations for 2008. In FY2011, the CFES ensemble system was developed, and the CFES-LETKF coupled system is near completion. In FY 2012, the CFES-LETKF development was completed, and data assimilation experiments were performed using the same data as the AFES-LETKF experiments. The CFES-LETKF experiments provided ensemble analyses of sea-surface temperature (SST), consistent with the atmospheric analyses.

In the component of mesoscale data assimilation, in FY2010, the WRF-LETKF system was developed and assessed with T-PARC observations in the case of Typhoon Sinlaku (2008) (1 paper published). In addition, we have made three fundamental achievements: 1) a new adaptive inflation method has been developed for improving the LETKF (1 paper published), 2) the impact of observation error correlations on data assimilation was examined (1 paper published), and 3) importance of the initial conditions in TC forecasts using the Japanese operational global system has been published (1 paper published). In FY2011, the ensemble sensitivity system to compute the impact of observations on forecasts has been developed and applied to the case of Sinlaku with particular focus on T-PARC dropsonde observations (1 paper accepted). In addition, we have made three major achievements: 1) satellite temperature and humidity profile data from the AIRS (Atmospheric Infrared Sounder) retrieval products have been assimilated and have shown significant positive impact on the track and intensity forecasts of Sinlaku (1 paper published), 2) the impact of ensemble perturbations of SST fields on Sinlaku's analysis was investigated (1 paper published), 3) the running-in-place (RIP) method to handle the issue of the EnKF spin-up was implemented and tested in an observing systems simulation experiment (OSSE), showing significant improvements of typhoon assimilation in a stage of rapid intensification (1 paper published). In FY2012, we have made six major achievements: 1) two-way-nested heteorgeneous system was developed for efficient higher-resolution analyses, 2) the RIP method was applied to the real case of Sinlaku (2008) and showed promising results, 3) an additional experiment was performed with perturbed SST from the CFES-LETKF experiments, 4) observation impacts were estimated for many TC cases during T-PARC 2008 and ITOP 2010 and were statistically analyzed, 5) a parameter estimation method using LETKF was developed and applied to estimate the air-sea exchange coefficients, and 6) a new formulation of the ensemble sensitivity method was developed (1 paper accepted).

In this three-year project, 10 peer-reviewed papers have been published or accepted so far, and 22 oral and 6 poster presentations were presented at international scientific meetings, including 5 invited.

RESULTS

The most significant achievement in FY2012 was the new development of the WRF-LETKF with two-way-nested heterogeneous grids. This allows analyzing multpile nested domains with a single LETKF step, rather than performing multiple LETKF steps for each nested domain. Figure 1 (a) illustrates an example of multiple nested grids. We can apply multiple LETKF steps to each nested domain separately, but instead, we have developed a system that can treat this heterogeneous grid structure with a single step of the LETKF, taking advantage of the local treatment of the LETKF algorithm. Using this system, we successfully analyzed the finer structure of Typhoon Sinlaku. Figure 1 (b) and (c) show sea-level pressure (SLP) contours (hPa) on top of precipitation (color shading, mm) at 0000 UTC, September 11, 2008. The 20-km analysis (Fig. 1 c) shows finer structure of Sinlaku than the 60-km analysis (Fig. 1 b). We find spiral rain bands and a clearer eye structure with the 20-km resolution. The results also indicated that the higher-resolution analysis could use more effectively the dropsonde data in the vicinity of the TC.

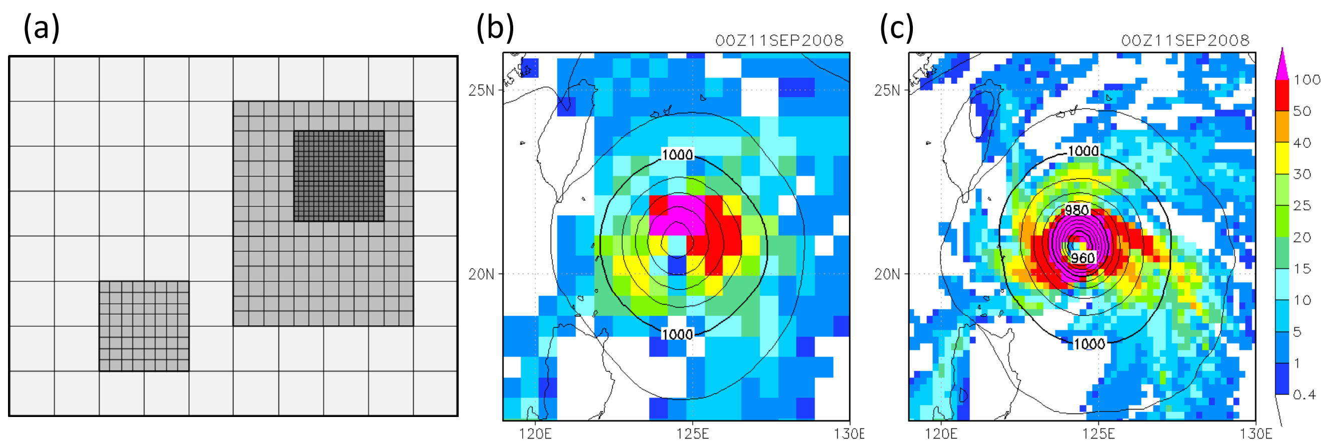

Fig. 1

Another notable achievement was obtained by applying the Running-In-Place (RIP) method to the real case of Sinlaku (2008). Figure 2 (right panel) shows Sinlaku's track forecasts initialized at 0600 UTC, September 6, 2008, with red (blue) curve indicating with (without) the RIP method. The RIP method made the forecast much closer to the observed best track (black), likely because the RIP method can make more effective use of the dropsonde data in the typhoon core region (red circles of Fig. 2 left panel). The RIP method showed a singificant improvement of the intensity forecasts, particularly in the rapidly-intensifying stage of Sinlaku.

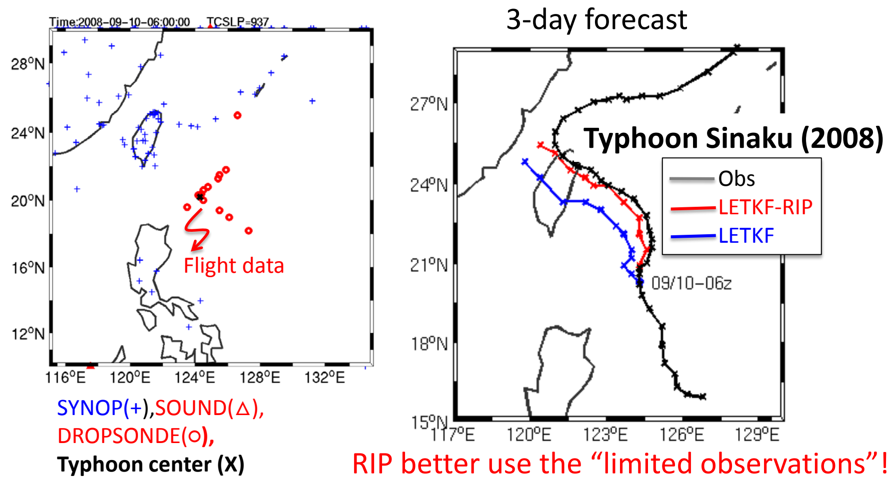

Fig. 2

We also completed the development of the CFES-LETKF system and performed data assimilation experiments. The initial results were very encouraging, showing ocean uncertainties consistent with the atmospheric analyses. We find generally larger near-surface ensemble spread in the atmosphere, as expected, which contributes to improving atmospheric analyses. We performed an additional WRF-LETKF experiment using the CFES-LETKF SST anlayses as the lower boundary conditions. Figure 3 shows SLP anlaysis contours (hPa) and SST ensemble spread fields (color shading, K) at 1200 UTC, September 12, 2008, just prior to the landfall to Taiwan, for SSTP (climatological SST perturbation that we performed last year) and CFES experiments. Apparently we can find the SST perturbation maximum corresponding to Sinlaku, in the wake region.

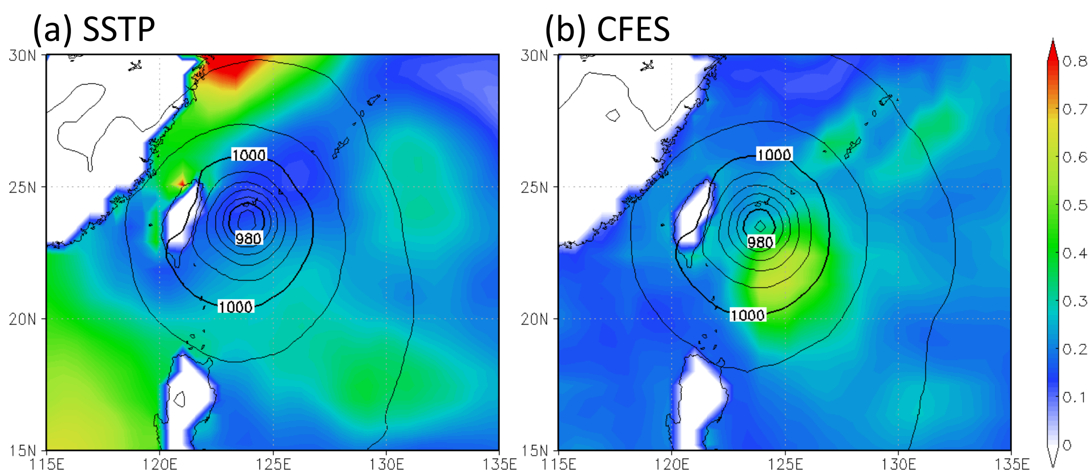

Fig. 3

We also made further investigations on observation impacts computed by the ensemble sensitivity analysis system that we developed last year. We computed the observation impacts of dropsonde observations during the T-PARC 2008 and ITOP 2010 field campaignes, and investigated overall statistics. Figure 4 shows the averaged impacts of dropsonde data during T-PARC 2008 (left) and ITOP 2010 (right), categorized into vertical levels for each variable (U, V, and T). We find general improvement of the forecasts due to the dropsonde data, although ITOP-2010 temperature data near the lower troposhere shows slight negative impact. This may be related to the model errors of the WRF boundary layer, particularly considering the vicinity of tropical cyclones. Figure 5 is another statistics, showing composites relative to the TC center location. The center point of Fig. 5 corresponds to the TC center (shown by the TC weather symbol), and the color shading indicates averaged impacts of dropsonde data at each location relative to the TC center. For example, the coordinate (2, 0) of Fig. 5 corresponds to the observed location 200-km east of the TC center. Overall, we find positive impacts, in particular, ITOP 2010 improved the forecasts everywhere, with maximum positive impact southeast of the TC center within a 300-km range. In T-PARC 2008, most improvements were brought by observations southwest of the TC center.

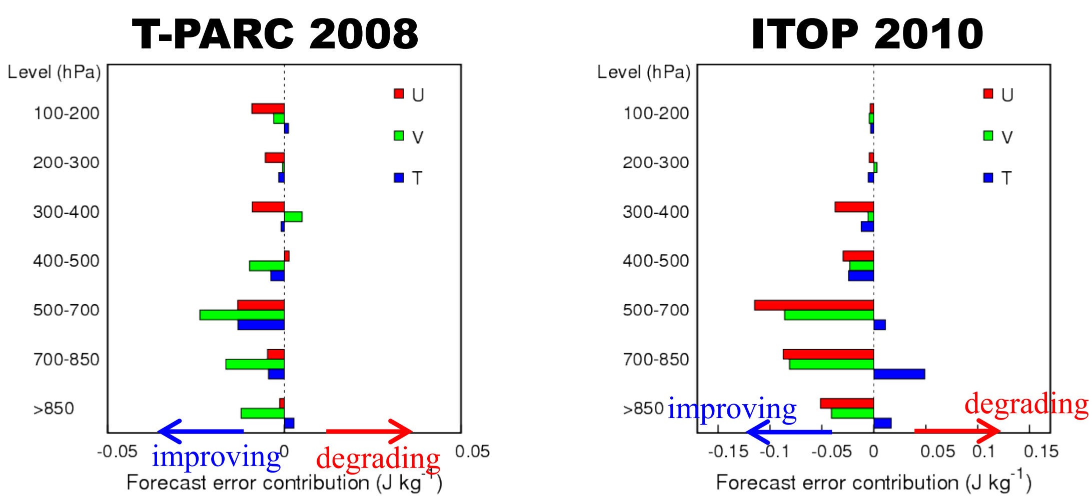

Fig. 4

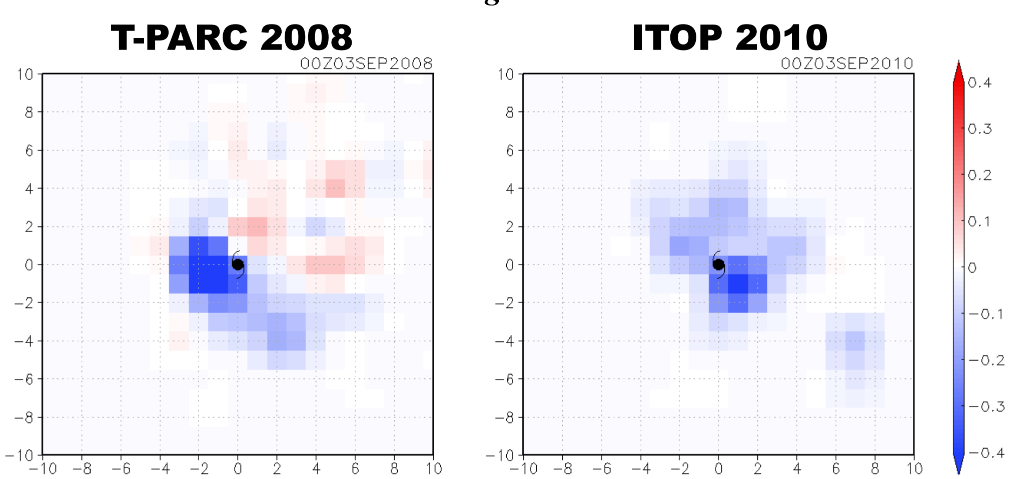

Fig. 5

We also investigated the sensitivity of air-sea exchange coefficients to Sinlaku's forecasts. We found that the moisture exchange coefficients have a major impact on both track and intensity forecasts. Figure 6 shows Sinlaku's best track data (track and intensity, red solid curves) and the range of forecasts with different parameter settings (grey-black curves). We applied a parameter estimation approach using the LETKF, and estimated the spatially-varying moisture exchange coefficients. Figure 7 shows the results of the horizontal distribution of the estimated parameter. The value 1.0 indicates the default WRF-model parameter, and the smaller (larger) values show less (more) effective moisture exchange. We could successfully esimate the spatially-varying exchange coefficients, and are currently investigating the impact on Sinlaku's forecasts due to the parameter estimation.

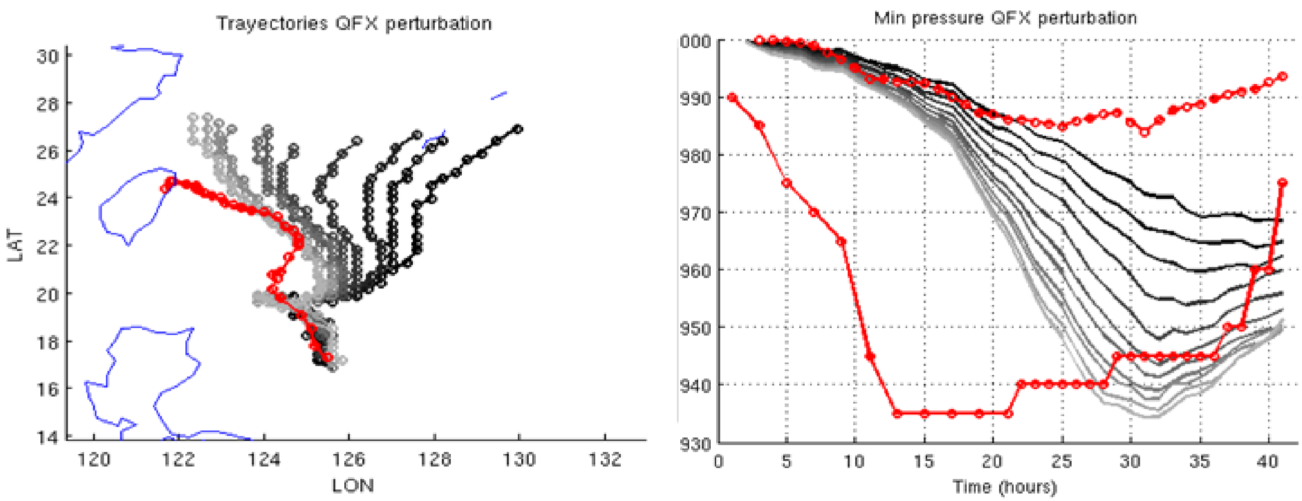

Fig. 6

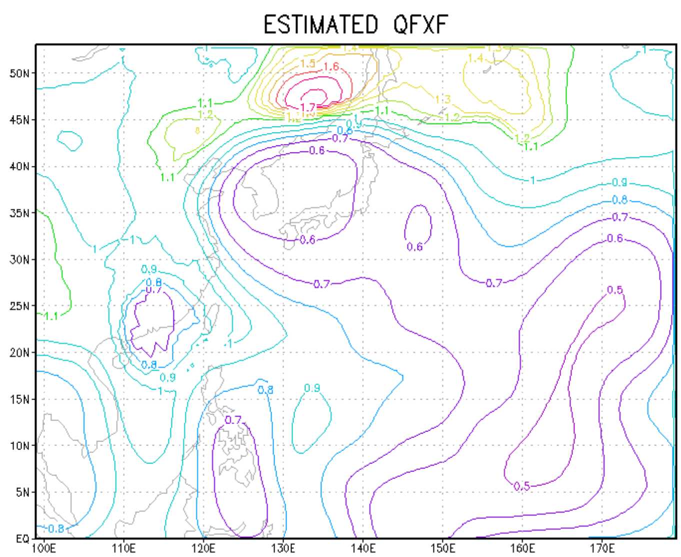

Fig. 7

IMPACT/APPLICATIONS

National Security, Economic Development, and Quality of Life

The goal of this project is to improve the LETKF and the prediction of TCs, with particular focus on the TC lifecycle evolution and intensity. Better prediction of TCs with quantitative measure of its uncertainty has the significant impact on National Security, Economic Development, and Quality of Life, since military operations, economic activities, and people's life are affected by extreme weather.

Science Education and Communication

Data assimilation provides a bridge between the nature and computer simulations, and the LETKF is a general and practical approach to data assimilation. This project aims to improve the LETKF, which may have potential impact on Science Education, particularly on emerging and rapidly expanding applied mathematics and scientific computing fields.

TRANSITIONS

National Security, Economic Development, and Quality of Life

The Japan Meteorological Agency (JMA) and INPE/CPTEC (Brazilian Institute for Space Research and Brazilian Weather Service) are developing the LETKF for possible future operations, and the findings from this project have been directly transferred to their preoperational systems. This is an important path of transitioning the achievements of this project to the operational NWP, which in turn benefits to National Security, Economic Development, and Quality of Life. We would like to seek similar paths to the US institutions.

Science Education and Communication

The LETKF system is widely available through the internet (http://code.google.com/p/miyoshi/), which has been used in Science Education for students and researchers at UMD and many other places worldwide, including the JMA, Tohoku University (Japan), University of Buenos Aires (Argentina), and INPE/CPTEC (Brazil). In addition, the fundamental improvements as a result of this project have been applied in many studies at the UMD and other places worldwide.

RELATED PROJECTS

There are several related and mutually beneficial projects.

1. The Tropical Cyclone Structure-2008 (TCS-08) program is sponsored primarily by the Office of Naval Research (ONR) with funding also from the National Science Foundation for shared aircraft resources. The objectives of TCS-08 address mechanisms and predictability of tropical cyclone formation, intensification, and structure change. The observation data are a key part of T-PARC and are assimilated in our NOPP project.
2. The Impacts of Typhoons on the Ocean in the Pacific (ITOP) program is also sponsored by ONR and is a multi-national field campaign that aims to study the ocean response to typhoons in the western Pacific Ocean. Our NOPP project is closely related and has mutual benefit. The new techniques pioneered with T-PARC/TCS-08 observations can be independently tested with the ITOP/TCS-10 observations.
3. The Japan Meteorological Agency (JMA), INPE/CPTEC, and German Weather Service (DWD) are developing the LETKF for possible future operations, and our achievements to improve the LETKF are beneficial to their development, and their results help us to know how our achievements apply to the real-world operational NWP.

4. Juan Ruiz (University of Buenos Aires, Argentina) uses the LETKF system for model's parameter estimation. He directly contributed to this study by applying his parameter estimation code to the WRF-LETKF system.
5. Prof. Shu-Chih Yang (Taiwan Central University) is testing her new "quasi outer loop" approach for TC data assimilation with encouraging results. She is a Co-I of our NOPP project, and this is clearly mutually beneficial.
6. Prof. Hong Li (Shanghai Typhoon Institute, China) has applied the ensemble sensitivity analysis method using the LETKF to a low-resolution global atmospheric model for assessing the impact of different types of simulated observations in ideal experiments. She is a Co-I of our NOPP project, and this is clearly mutually beneficial.
7. Steve Penny (UMD graduate student) completed his doctoral dissertation based on the LETKF coupled with the MOM2 global ocean model to perform advanced ocean data assimilation. His current results indicate a very large improvement when compared with SODA (Simple Ocean Data Assimilation), a reanalysis based on a standard state-of-the-art 3D-Var data assimilation system. The adaptive inflation scheme improved his MOM2-LETKF results significantly.
8. Steve Greybush (UMD graduate student) completed his doctoral dissertation this Spring has also benefited from the adaptive inflation in his LETKF application to Mars atmosphere, with very encouraging results.
9. Ji-Sun Kang (UMD postdoctoral researcher) has benefited from adaptive inflation in the estimation of the surface fluxes of carbon from atmospheric CO_2 data assimilation. Her experiments led to the concept of "variable localization" that in turn improves the LETKF.
10. Luciano Pezzi (INPE/CPTEC, Brazil) uses the LETKF for regional ocean data assimilation and had very encouraging results with adaptive inflation.

PUBLICATIONS

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HONORS/AWARDS/PRIZES

PI Miyoshi was selected in a very competitive search for Team Leader (equivalent to the full professor level) of the newly established Data Assimilation Research Team, RIKEN Advanced Institute for Computational Science, located in Kobe, Japan.